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1 Introduction

Siltation of mud and silt in harbour basins is a problem that exists as long as harbours exist and is related to their basic function, providing shelter by creating quiescent conditions. Many harbour entrances have been found to be difficult for ships to navigate owing to siltation in the entrance zone.

Important questions for the harbour authorities are:

- what is the mean annual dredging volume and what is the amount of dredging in the entrance area?
- what is the composition and contamination of the deposited materials?

The amount of siltation appears to be strongly related to the physical and environmental conditions and the geometric configuration of the harbour entrance. In particular, the types of flow related to fluid density variations are extremely important, which are herein defined as: salt water flow
(basins along the seashore), brackish water flow (basins along estuary mouths and tidal rivers) and fresh water flow (basins along non-tidal river, canals and lakes). Wind and wave-induced flows and stirring of sediments will play an important role when the basin is situated along a sea or a lake (large-scale outside area).
Analysis of observed siltation rates in various environmental conditions shows that harbour siltation in fresh water conditions is much less (factor 5) than in salt and brackish water conditions (**Nasner, 1992**). The generation of stratified flow with a clear salt water wedge (vertical circulation) is a well known phenomenon in the tidal zone of major rivers (tidal volume about equal to fresh water volume over tidal period). The maximum silt and mud concentrations are generally found in the area where the edge of the salt water front is moving up and down the river channel. This zone where soft fluid mud layers are formed due to deposition at slack tides (especially neap tides) is known as the turbidity maximum. Harbour basins situated inside this zone generally suffer from heavy siltation due to the presence of fluid mud layers penetrating into the basins. The deepening of harbour approach channels to accommodate larger vessels has often resulted in more landward penetration of the tide and associated turbidity maximum zone causing increased siltation in basins which previously where outside the turbidity maximum zone (**Kendrick, 1994**).
An important environmental aspect related to harbour siltation is the degree of contamination of the deposited material, which highly determines the dredging and cleaning costs involved and thereby the economic profits. The origin of the contamination may be a local (industry along the basin) or a non-local source. In the latter case it may be attractive to minimize the annual sedimention volume by special structures near the entrance of the basin to reduce the sediment input as much as possible or to perform agitation dredging.

2 Flow patterns and water exchange in harbour basins

The fluid volume entering or leaving the entrance of a harbour consists of the following contributions:

- filling and emptying (advective processes) of the tide (V_t),
- horizontal eddy circulation (diffusive processes) generated in the entrance by the main flow outside the entrance (V_h),
- vertical circulation in the entrance generated by density differences between the fluid inside and outside the basin (V_d);
- fresh water discharged into the basin by a small river or drainage water ($V_{d,a}$).

The total water exchange (volume passing the entrance opening) per tide is: $V_e = V_t + V_h + V_d + V_{d,a}$

Basically, these complicated three-dimensional flow patterns inside and outside harbour basins can be determined from experiments in laboratory scale models, by detailed field measurements and increasingly by three-dimensional mathematical models . The most accurate results are still obtained by performing tests in a laboratory scale model, because this approach allows the detailed representation of the basin geometry and related turbulent vortex structures. Furthermore, the effectiveness of control structures such as current deflection walls, anti-silt curtains, sills, etc. can be tested properly. A recent example of such a study is the design of the current deflection wall for one of the berthing basins (Parkhafen) of the Port of Hamburg (**Delft Hydraulics, 2001**).

Mathematical computation of the flow pattern near harbour basins requires the application of a three-dimensional model including terms to represent density gradient effects in estuarine conditions (tidal flow in combination with fresh water outflow). Reliable and accurate quantitative results are difficult to obtain because the models cannot sufficiently reproduce the flow separation and eddy generation processes in the basin entrance.

Often drainage water is discharged into the harbour basin during rainy periods resulting in the supply of a considerable fresh water volume. In some cases a small river outlet (discharge Q_r) is present, filling the basin from the landside.

The total exchange volume per tide will be affected, as follows:

- decrease of the tidal volume V_t with $V_r = Q_r\, T_{flood}$ during the flood phase of the tide;
- slight increase of the horizontal circulation volume due to reduction of the tidal filling volume;
- increase of the vertical circulation volume due to decrease of the water density inside the basin; the fresh water will pass the basin through the upper part of the water column and will be partly mixed with the denser fluid in the lower part of the water column (mixing processes); hence, the density difference ($\Delta\rho_{max,o}$) will depend on the magnitude of V_r in relation to the total volume V (below LW level) of the basin.

Wave energy can penetrate into harbour basins by direct propagation of energy into the basin from directions normal to the entrance line and by diffractional processes from other directions. Wave diffraction is transfer of wave energy in lateral direction (normal to wave propagation direction) along the wave crest. As diffractional wave theory is too complicated to compute the wave height patterns in most practical basin geometries and irregular bottoms, the wave height distribution in a harbour basin generally is determined by means of tests in a laboratory scale model. The measured wave heights are expressed as a percentage of the incoming wave height outside the entrance. The geometry can be optimized to reduce the wave heights in the basin as much as possible.

Sediments (mud, silt and sand) stirred up from the bed by the action of currents and waves outside the basin entrance can be transported into the basin by (generally weak) currents due to tidal filling and horizontal circulation. Inside the basin the wave height generally decreases rapidly resulting in a reduction of the sediment transporting capacity and hence in siltation in the entrance area, which may be problematic with respect to navigation. Often, a sediment trap (buffer zone) is situated in the entrance area to keep the navigation depth at the required level and to reduce the maintenance dredging frequency.

3 Siltation processes in harbour basins

3.1 Observed siltation rates

Annual siltation values from various harbour sites have been summarized in **Tables 3.1** and **3.2**.

Harbour sites **Netherlands**	**Distance to open sea** **(km)**	**A_{basin}** **(10^6 m²)**	**$A_{entrance}$ below MSL** **(m²)**	**Tidal range and duration** **(m)**	**Peak tidal current outside entrance u_o** **(m/s)**	**Concentration outside (yearly-average) c_o** **(kg/m³)**	**Density difference $\Delta\rho_{o,max}$** **(kg/m³)**	**Sedimentation volume per year (dredging volume)** **(10^6 m³/yr)**	**Sedimentation thickness** **(m/yr)**
Braakman, Terneuzen, Western Scheldt Estuary (DH, 1986)	15	1.1	A=5900 (b=420, h_o=14 m)	3-4 (12 h)	1.1	0.05-0.1 (mud, 10% sand) w_s=0.1-0.5 mm/s	1.5	1.1	1
Harlingen 1) Wadden Sea (DH, 1998)	20	0.2-0.85	A= 615-1010 (b= 110-150, h_o=6-7.5)	1.5-2 (12 h)	1-1.5	0.05-0.4 (mud, 10% sand)	0.5	0.2-0.85 (over 47 years; 1950-1997)	1
Botlek New Waterway, Rotterdam (DH, 1989)	20	2.8	A=5000 (b=320, h_o=15.5 m)	1.75 (12 h)	1	0.1-0.15 (mud)	4	2-3.5 (1960-1985)	0.7-1.25
Den Helder 2) Naval Basin Texel Inlet (DH, 1993)	3	0.8-1.4	A=2900-3500 (b= 290-350, h_o=10 m)	1.2-1.5 (12 h)	1.25	0.05-1.0 (mud, 5-10% fine sand)	1-1.5	0.5-1.0 (1955-1992)	0.6-0.7
Delfzijl 3) Eems-Dollard, Estuary, Wadden Sea (DH, 1999)	20	2.2	A=1700-2400 (b=200-240, h_o=8.5-10 m)	3-3.5 (12 h)	0.7-1.2	0.15-0.3 (mud) w_s=0.1 mm/s	2-4	1.4-2.6 (1982-1997) dry bulk density of 250-450 kg/m³	0.7-1.2
Oudeschild Island of Texel, Wadden Sea (DH, 2000)	7	0.075-0.105	A=180-210 (b=32-38, h_o=5.5 m)	1.4 (12 h)	1-1.2	0.1 (mud)	0-0.5	0.01-0.016 (1973-1999)	0.1-0.15
IJmuiden; New 4) North Sea (Rakhorst et al., 1982; De Kok, 2001)	0	4	A=1000 (b=500, h_o= 20 m)	1.5-2.0	1-1.3	0.05-0.1 (mud)	0	0.65 sand 3.2 mud	0.15 sand 0.8 mud
IJmuiden; Old 5) North Sea (Van der Made, 1957)	0	1.5	A=3750 (b=250, h_o= 15 m)	1.5-2.0	1	0.05-0.1 (mud)	0	0.3 sand 1.2 mud	0.2 sand 0.8 mud
Scheveningen 5) North Sea (De Roo, 2002)	0	0.26-0.28	A=1800 (b=190. h_o= 20 m)	1.5-2.0	0.8	0.05-0.1	0	0.07-0.09 s 0.22-0.34 m	0.25-0.35 0.8-1.25

1) Fresh drainage water outflow in harbour basin of about 0.3-0.5 10^6 m³/tide (sediment concentration of 0.005 kg/m³)
2) Fresh drainage water outflow in harbour basin of about 200-300 10^6 m³/year (sediment concentration of 0.005 kg/m³)
3) Fresh drainage water outflow in harbour basin of about 400 10^6 m³/year (sediment concentration of 0.005 kg/m³)
4) Fresh drainage water outflow in harbour basin of about 3000 10^6 m³/year (=about 4 10^6 m³/tide; 710 tides per year)
5) Fresh drainage water outflow in harbour basin (volume is not known)

Table 3.1 *Observed siltation rates in harbour basins in The Netherlands*

Based on the data of **Tables 3.1** and **3.2**, the siltation volumes mainly depend on:

- entrance area ($A_{entrance}$);
- sediment input concentration (yearly-average value, c_o);
- density difference ($\Delta\rho_{max,o}$).

Most harbour basins show an annual siltation thickness (ratio of siltation volume and basin area) in the range of 0.5 to 1 m (basin-averaged values).
The annual siltation layer is relatively large (0.5 to 1 m) in conditions with major density current effects (Delfzijl and Botlek harbour basins, The Netherlands) and relatively small (0.1 to 0.3 m) in conditions with no or minor density currents and low sediment concentrations (**c_o**<0.1 kg/m^3), as occurring in Bintulu (Indonesia), Oudeschild (The Netherlands) and Parkhafen (Germany). Other causes of relatively small siltation rates in harbour basins may be the presence of a deep access channel, a silt trap or an outer basin (Bintulu), where most of the sediments are trapped.

Generally, the siltation is largest near the entrance where relatively coarse sediment fractions (0.03 to 0.1 mm) are deposited; siltation rates are smallest near the end of the basin where the finest fractions (0.05 to 0.03 mm) are deposited.
For example, analysis of the siltation patterns in the basins of the harbour of Hamburg shows that 60% to 85% of the total dredging volume is deposited in the entrance region of the basins (**Christiansen, 1996**). The siltation pattern in the navigation channel between the two jetties of the harbour basin of IJmuiden (Netherlands) shows the presence of fine sands., wheare as mud and silt are present inside the harbour basin.

Harbour sites **Europe, Asia, USA**	**Distance to open sea** **(km)**	**A_{basin}** **(10^6 m^2)**	**$A_{entrance}$ below MSL** **(m^2)**	**Tidal range and duration** **(m)**	**Peak tidal current outside entrance u_o** **(m/s)**	**Concentration outside (yearly-average) c_o** **(kg/m^3)**	**Density difference** **$\Delta\rho_{o,max}$** **(kg/m^3)**	**Sedimentation volume per year (dredging volume)** **(10^6 m^3/yr)**	**Sedimentation thickness** **(m/yr)**
Um Qasr, Khor al Zubair, (Shatt al Arab), Irak (DH, 1981)	7	1.2	A=4100 (b=300, h_o=13.5 m)	2.2-3.7 (12 h)	1-2	0.2-0.4 (soft clayey silt) w_s=0.1-0.3 mm/s	1.5	1.3	1.1
Bintulu Port $^{1)}$ Sarawak, Indonesia (DH, 1991)	0-1	0.82	A=1875 (b=125, h_o=15 m)	1 (24 h)	0.1	0.05 (mud)	1-2	0.077 (1982-1988)	0.1
New Mangalore Port Kerala coast, ZW India (DH, 1994)	0-1	1.1	A=3400-3700 (h_o=11.5-13.5 m)	1 (12 h)	0.1-0.3	0.05 0.4 (monsoon period)	0-0.3 (river outlfow at 10 km)	0.9 (1982-1997)	0.8
Mayport Naval Basin, Florida, USA (Headland, 1991)	3	0.5	A=2300 (b=185, h_o=12.5)	1.5 (12 h)	0.7	0.01-0.04 (mud; 0.02 mm)	1-3	0.38	0.75
Parkhafen Hamburg, Germany (DH, 1992, 2001)	100	1.5	A=8650 (b=515, h_o=16.8)	3.2 (12 h)	1	0.05-0.1	0	0.13-0.52 (1977-1995)	0.1-0.35

$^{1)}$ Fresh river water outflow in harbour basin of about 0.15 10^6 m^3/day (sediment concentration of 0.01 kg/m^3)

Table 3.2 *Observed siltation rates in harbour basins in Europe, Asia and USA*

The importance of the sediment input concentration can be demonstrated by comparing the siltation volumes of the harbours of Delfzijl and Mayport, which have about the same entrance area and density difference. The siltation volume of the Delfzijl harbour is much larger due to the larger sediment input concentration.

The siltation rate can also be expressed per unit area of the entrance opening (ratio of siltation volume and entrance area), yielding the following ranges:

- 50 to 200 (m^3/m^2) for $\Delta\rho_{o,max} = 0$ to 0.5 kg/m^3;
- 200 to 600 (m^3/m^2) for $\Delta\rho_{o,max} = 0.5$ to 2 kg/m^3;
- 600 to 1000 (m^3/m^2) for $\Delta\rho_{o,max} = 2$ to 4 kg/m^3.

The lower values (50, 200 and 600 m) occur for relatively small sediment input concentrations (0.05 to 0.1 kg/m^3); the higher values (200, 600 and 1000 m) for relatively large sediment concentrations (0.2 to 0.3 kg/m^3).

Nasner (1992) has presented a detailed overview of the siltation volumes (based on long-term observations over 10 to 15 years) of most harbour basins in the north of Germany. The results are presented in **Table 3.3**. The basins can be classified into three groups based on the salinity range of the water, as follows:

- salt water: Büsum and Wilhemshaven;
- brackish water: Cuxhaven, Emden, Bremerhaven and Brunsbüttel;
- fresh water: Bremen and Hamburg.

Analysis of the results shows the following characteristics:

Salt and brackish water basins

- the mean siltation rates vary between 1 and 2 m per year; these values refer to basin-averaged values; the siltation rates in the entrance area generally are 2 to 3 times larger (up to 5 m/year);
- the siltation rates in the summer are 1.5 times larger than those in the winter due increased biomass production and increased salinity in the summer (smaller fresh water discharges in summer);

Fresh water basins

- the mean siltation rates vary between 0.3 and 0.4 m per year; these values refer to basin-averaged values; the siltation rates in the entrance area generally are 3 to 10 times larger (up to 3 m/year in Hamburg);
- the siltation rates increase with decreasing fresh water discharge (river) in Hamburg as a result of the increased tidal discharges (reduced river discharges) and increased tide-induced mud concentrations during low river discharges;
- the siltation rates increase with increasing fresh water discharge (river discharge) in Bremen, because the mud concentration increases from 20 mg/l at low discharge (100 m^3/s) to 150 mg/l at high discharge (1000 m^3/s);
- the siltation rates increase with increasing basin depth;
- the siltation rates decrease with decreasing B/L ratio (B= entrance width, L= basin length); siltation of 0.1 m/y for B/L=0.04 and 0.45 m/y for B/L=7 in Bremen.

Based on the available data, it is clear that the siltation rate in fresh water basins is substantially smaller (factor 3 to 5) than that of salt or brackish water basins.

Another example of the effect of salinity on siltation is presented by **Naik et al. (1983)** for the Port of Cochin on the west coast of India. The total annual maintenance dredging volume is about 3.5 million m^3; about 70%

in the main approach channel outside the harbour area and 30% in the interior harbour channels. Nearly 70% of the siltation in the interior channels takes place during the south-west monsoon season (rainy season) from June to September. During this period the tidal inflow is highly stratified with a clear salt wedge owing to the increase of the fresh water outflow of various rivers. The total influx during the average spring tide of 0.8 m is approximately 90 million m^3 per tide, whereas the total average fresh water outflow is about 125 million m^3 per tide. These conditions result in the formation of a salt water wedge and density currents in the harbour channels. The mud concentrations at the entrance of the interior channels are much larger during the flood tides than during the ebb tides. Furthermore, the mud concentrations are relatively large at spring tide compared to neap tide. This information clearly suggests that the muddy siltation materials originate from the sea as a result of net landward inflow of sediments due to vertical circulation effects.

Harbour site	**Salinity (promille)**	**Tidal range (m)**	**Basin area (m^2)**	**Mean river discharge (m^3/s)**	**Entrance depth (m)**	**Sedimentation layer (m/year)**	**Sedimentation volume (m^3/year)**
Büsum within 1 km from North Sea (1 basin)	salt	3.3	$0.026\ 10^6$	none	8	1.3	$0.034\ 10^6$
Wilhelmshaven in Jade Bay at 10 km from sea (1 basin)	salt	3.8	$0.73\ 10^6$	none	8	1.5	$1.1\ 10^6$
Cuxhaven in mouth of Elbe at 1 km from sea (2 basins)	16.5 brackish	3.0	$0.185\ 10^6$	720	8-9	1.1	$0.2\ 10^6$
Emden in mouth of Ems, at 5 km from sea (2 basins)	5.3 brackish	3.1	$0.24\ 10^6$	75	8-10	2.3	$0.56\ 10^6$
Bremerhaven in mouth of Weser at 10 km from sea (5 basins)	8.6 brackish	3.6	$0.36\ 10^6$	315	9-11	1.35	$0.49\ 10^6$
Brunsbüttel in mouth of Elbe at 15 km from sea (3 basins)	2.8 brackish	2.8	$0.79\ 10^6$	720	10-11	2.0	$1.58\ 10^6$
Bremen along Weser at 50 km from sea (about 10 basins)	fresh	3.8	$1.9\ 10^6$	300	8-12	0.3	$0.57\ 10^6$
Hamburg along Elbe at 100 km from sea (about 15 basins)	fresh	3.0	$6.1\ 10^6$	720	15-17	0.35	$2.2\ 10^6$

Table 3.3 *Siltation volumes of tidal harbour basins in north of Germany (Nasner, 1992, 1997)*

Fluid mud layers have been observed in many harbour basins around the world, which are situated within the tide-induced salinity zone. The high-concentration fluid mud layers are formed as a result of:

- flocculation and (hindered) settling of suspended sediments in the water column;
- settling of sediments and flocs resuspended by agitation dredging processes;
- settling at a larger rate than the sinking of the bed by consolidation processes;
- inflow of turbidity layers from the main channel by density-induced and gravity-induced forces (if bed of basin is at same level of lower than bed of main channel)

3.2 Prediction of siltation volumes

Basically, the following methods can be applied to estimate the siltation in a harbour basin:

- laboratory scale models including tidal effects, density-driven effects (saline sea water and fresh river discharges) and sediment deposition effects (tracer studies);
- three-dimensional mathematical models describing the flow patterns, the fluid density patterns and the sediment concentration patterns in the basin;
- simplified semi-empirical methods schematizing the most important physical processes of siltation in a harbour basin.

1. Laboratory scale models

The most detailed information of the physical processes involved (flow and fluid density patterns) can only be obtained from measurements in a laboratory scale model in combination with field measurements (boundary conditions). Tide-induced and density-induced flows should be included, which means that both the saline inflow from the sea as well as the fresh water inflow from land (river discharge) should be represented properly. Detailed calibration is required to determine the proper tidal storage area and the bed roughness in the main channels. The existing and future harbour basin configurations can be built in and studied. The exchange volume passing the harbour entrance can be determined from detailed flow velocity measurements in combination with salinity measurements. Tracer studies using dye and/or light-weight materials can be done to determine the sediment deposition patterns in the harbour basin (trapping efficiency). Structures and measures (improvement of entrance geometry) to reduce the siltation rates can be tested rather well (comparatively) in a laboratory scale model.
However, the translation of the trapping efficiency in the laboratory scale model to a realistic trapping efficiency for natural conditions is problematic due to scale effects. Furthermore, field data of the sediment input concentration is essential to finally estimate the annual deposition in the basin.
The best option often is to use the laboratory results as input data and calibration data of a three-dimensional mathematical model approach or if this is not feasible to use the laboratory data as input for a schematized semi-empirical method.

2. Three-dimensional mathematical model

The accurate representation of the complicated flow and sediment transport patterns outside and inside a harbour basin basically requires a three-dimensional mathematical model consisting of:

- continuity and momentum equations for fluid velocity (see **Van Rijn, 1993**; Chapter 12),
  - free surface representing tidal variations,
  - sophisticated turbulence model representing the mixing properties of the flow (including turbulence damping effects due to presence of sediments and density differences);
- continuity equation (advection-diffusion equation) for salinity variations;
- continuity equation (advection-diffusion equation) for sediment concentrations (including exchange mechanism at bed boundary, hindered and flocculated settling resulting in concentration-dependent settling velocity).

In tidal flow conditions the model domain needs to include a considerable portion of the adjacent sea for proper representation of the tidal motion including salinity and sediment concentration variations. Wave modelling is often required to simulate the wave-induced stirring of mud from the seabed into the main body of the flow.
Although present-day computer power is continuously progressing, these types of computations still require excessive computing times limiting the number of runs. Hence, extensive sensitivity studies can only be done for major projects (Harbour of Antwerp, **Delft Hydraulics, 2002-2003**).
An important advantage of the application of mathematical models is that vertical and horizontal gradients of the fluid velocities and the sediment concentrations can be taken into account. The vertical distribution of the mud concentrations is particularly important. Field data sets show that the mud concentrations near the bed are substantially larger than those near the surface (factor 3 to 5), which may have a strong impact on the predicted siltation rates.

3. Semi-empirical box method

Model description

The time-dependent behaviour of the suspended sediment concentration in a basin (with a water depth equal to that outside the basin) can easily be represented by schematizing the basin to a simple box (**Figure 3.1**). An additional storage basin 2 may be present at the end of the harbour basin 1. The banks of the harbour basin may consist of mud flats/banks with lateral inflow of mud. The mud concentration is assumed to be uniform over the water depth.

Flood flow between LW and HW: water will enter harbour basin due to the rising water level.

Ebb flow between HW and LW: water will leave harbour basin due to the lowering water level .

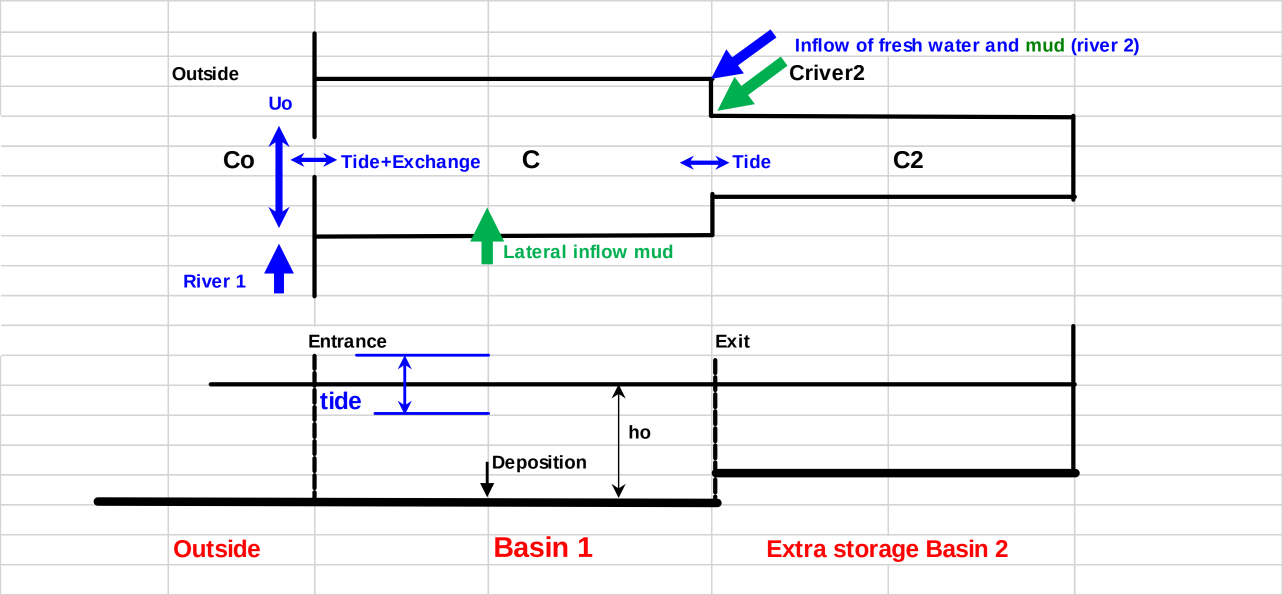

Figure 3.1 *Schematized harbour basin (top view and side view)*

The sediment mass balance in harbour basin 1 can be expressed as:

Flood flow:

$$A\, d(hc)/dt = (Q_{tide1}+Q_{hor}+Q_{vert1}+Q_{vert2})c_o - (Q_{hor}+Q_{vert1}+Q_{vert2})c - A\, c\, w_{s,eff} - Q_{tide2}\, c + pQ_{river}(c_{river2} - c) \qquad (3.1)$$

$$= Q_{tide1}\, c_o + Q_{hor}\, (c_o - c) + (Q_{vert1} + Q_{vert2})(c_o - c) - A\, c\, w_{s,eff} - Q_{tide2}\, c + p\, Q_{river}\, (c_{river2} - c)$$

Sediment concentration c_o will enter basin by tidal filling, horizontal and vertical exchange,
Sediment concentration c will leave basin at entrance by horizontal and vertical exchange and river flow,
Sediment concentration c will be deposited on bottom of basin by effective settling,
Sediment concentration c will leave basin at exit (to storage basin 2),
Sediment concentration c_{river2} will enter basin due to river inflow (2).

Ebb flow:

$$A\, d(hc)/dt = (Q_{hor}+Q_{vert1}+Q_{vert2})c_o - (Q_{tide1}+Q_{hor}+Q_{vert1}+Q_{vert2})c - A\, c\, w_{s,eff} + Q_{tide2}\, c_2 + p\, Q_{river}\, (c_{river2} - c) \qquad (3.2)$$

$$= -Q_{tide1}\, c + Q_{hor}\, (c_o - c) + (Q_{vert1} + Q_{vert2})\, (c_o - c) - A\, c\, w_{s,eff} + Q_{tide2}\, c + p\, Q_{river}\, (c_{river2} - c)$$

Sediment concentration c_o will enter basin by horizontal and vertical exchange,
Sediment concentration c will leave basin by tidal emptying, horizontal, vertical exchange and river flow,
Sediment concentration c_2 will enter basin from storage basin ($c_2 = \alpha c_o$ with $\alpha \cong 0.1$ to 0.5),
Sediment concentration c will be deposited on bottom of basin by effective settling,
Sediment concentration c_{river} will enter basin due to river inflow (2).

The water discharges can be represented as:

Flood: $Q_{tide1}=(A_{basin1}+A_{basin2})\, d\eta_o/dt$
$Q_{tide2}=(A_{basin2})\, d\eta_o/dt$
$Q_{hor}= f_{1,flood}\, b\, h\, u_o$
$Q_{vert1}= 0.5\, f_3\, b\, h\, [(\Delta\rho_o/\rho_o)gh]^{0.5}$
$Q_{vert2}= p\, (f_{mixing} - 1)\, Q_{river2}$
Ebb: $Q_{tide1}=(A_{basin1} + A_{basin2})\, d\eta_o/dt$
$Q_{tide2}=(A_{basin2})\, d\eta_o/dt$
$Q_{hor}= f_{1,ebb}\, b\, h\, u_o$ (generally $f_{1,ebb} = 0$; no eddy generation during ebb)
$Q_{vert1}= 0.5\, f_3\, b\, h\, [(\Delta\rho_o/\rho_o)gh]^{0.5}$
$Q_{vert2}= p\, (f_{mixing} - 1)\, Q_{river2}$

The flood period is defined as the period with a positive value of $d\eta_o/dt$ (rising water level starting at t=0). Based on this, the basic tidal parameters can be represented, as:

$\eta_o = -\eta_{o,max} \cos(\omega t)$
$u_o = u_r - u_{o,max} \cos(\omega(t+\varphi))$
$\Delta\rho_o = -\Delta\rho_{o,max} \cos(\omega t)$
$c_o = c_{o1} - c_{o2} \cos(\omega t)$

The settling velocity is given by:

$$w_{s,eff} = \alpha_{reduction}\, w_{s,o}$$

with:
A_{basin1} = area harbour basin (input), A_{basin2}= area storage basin (input),
η_o = tidal water level to mean Sea Level (input), $\eta_{o,max}$ = amplitude value,
u_o = depth-averaged river+tidal velocity outside basin entrance (input),
$u_{o,max}$ = amplitude value of tidal velocity outside and parallel to the entrance (input),
u_r = depth-averaged steady river velocity outside and parallel to the entrance (input),
φ = phase shift tidal velocity with respect to vertical tide (input $\cong$ 0 to 3 hours earlier),
b = width of entrance (input),
b_{basin} = width of harbour basin (input),
$h= h_o+\eta_o$=water depth (outside and inside), h_o= water depth below Mean Sea Level (constant value; input),
Q_{tide1} = tidal discharge through entrance,
Q_{tide2} = tidal discharge through exit,
Q_{hor} = exchange discharge due to horizontal circulation at entrance,
Q_{vert1} = exchange discharge due salinity circulation (absolute value),
Q_{vert1} = exchange discharge due to fresh water river inflow at entrance,
c = depth-averaged concentration in basin (computed),
c_o = depth-averaged concentration outside basin (input),
c_2 = depth-averaged concentration in storage basin (input),
c_{01} = constant mud concentration outside entrance,
c_{02} = amplitude of variational mud concentration outside entrance,
$w_{s,o}$ = settling velocity in still water (input),
$\alpha_{reduction}= [1-(u_{basin})^2/(u_{critical,dep})^2][1-2(H_s/h)]$= reduction factor related to flow turbulence and wave motion,
$u_{basin} = Q_{tide1}/(h\ b_{basin})$= flow velocity in basin,
$u_{critical,\ dep}$= critical flow velocity for deposition (input $\cong$ 0.3 m/s; use large value of 10 m/s for no reduction),
H_s/h = relative wave height in basin (input $\cong$ 0.05 to 0.15), use $H_s/h=0$ for no reduction,
$f_{1,flood}$ = horizontal exchange coefficient during flood (input $\cong$ 0.025),
$f_{1,ebb}$ = exchange coefficient during ebb (input $\cong$ 0),
f_3 = vertical exchange coefficient (= 0.3),
$\Delta\rho_o$ = fluid density difference outside-inside (input), $\Delta\rho_{o,max}$ = amplitude value (input),
ρ_o = fluid density outside (input),
p = percentage of time with river inflow in basin (input),
f_{mixing} = mixing factor (input),
Q_{river2} = fresh water river inflow in basin (input),
c_{river2} = depth-averaged mud concentration in river 2,
ρ_d = dry bulk density of sediment deposits (input),
$T_{mud,lat}$ = lateral mud transport along bank bottom (if basin bank is a mud flat),
L_m = length of mud flat with lateral mud inflow.

The total exchange of water (inflow and outflow) across the basin entrance due to large-scale horizontal eddies and due to fluid density differences is zero. The volume of inflowing water is always equal to the volume of outflowing water in the case of exchange flows. As the mud concentration inside the harbour basin (c) is smaller than that outside (c_o) the basin, there is a continuous inflow of mud into the basin, both during flood and ebb flow.
If the mud concentration inside the basin is larger than that outside the basin due to agitation dredging (bed stirring), there is net outflow of mud due to the tidal and exchange currents. Agitation dredging can be simulated by using a high initial mud concentration inside the basin.

The incoming annual sediment volume (m^3 per year) through the basin entrance and exit is given by:

$$V_{s,in}= [N_{tides}/\rho_d]\ [{}_{flood}\sum\{Q_{tide1}\ c_o\ \Delta t\} + {}_{ebb}\sum\{Q_{tide2}\ c_2\ \Delta t\} + {}_{tide}\sum\{(Q_{hor}+Q_{vert})\ (c_o\text{-}c)\ \Delta t\} + {}_{tide}\sum\{T_{mud,lat}\ L_m\ \Delta t\} + {}_{tide}\sum\{p\ Q_{river}\ C_{river}\ \Delta t\}] \qquad (3.3)$$

The outgoing annual sediment volume (m^3 per year) through the basin entrance and exit is given by:

$$V_{s,out}= [N_{tides}/\rho_d]\ [{}_{ebb}\sum\ \{Q_{tide1}\ c\ \Delta t\} + {}_{flood}\sum\ \{Q_{tide2}\ c\ \Delta t\} + {}_{tide}\sum\{p\ Q_{river}\ c\ \Delta t\}] \qquad (3.4)$$

The net annual deposition volume inside the basin can be determined as the difference of the incoming and outgoing mud transport rates across the entrance (1) and exit (2) of the basin, yielding:

$$V_{s,deposition=}= V_{s,in} - V_{s,out} \qquad (3.5)$$

The annual siltation layer thickness can be expressed as:

$$\delta_s = V_{s,deposition}/A \qquad (3.6)$$

If the waterdepth inside the basin is negative due to drying out (tidal amplitude larger than water depth to MSL), then the water depth is set to 0.1 m (if h<0, h=0.1 m).

The effective settling velocity represents the net vertical settling effect due to downward settling in still water and upward diffusion due to turbulent fluid motions and surface waves in the basin.
If necessary, the effective settling velocity can be related to the concentration to include the flocculation effect ($w_{s,eff}= k\ c^n$).

This box-method is especially suitable for relatively small basins with an approximately rectangular planform, wherein the deposition layer is approximately uniform over the length and width of the basin.

Equations (3.1) to (3.6) can be solved numerically for given boundary conditions, see **Excel-programme SEDHAR.xls**. The time derivative of the concentration is taken at time t, using the concentration c from the previous time t-Δt.
The results of sensitivity computations show that the siltation rate increases almost linearly with the mud concentration (c_o) outside the harbour basin.

Practical application 1: harbour basins along side a tidal river/coastal flow
The box-method (**SEDHAR.xls**) has been used to compute the siltation volumes in the harbour basins of Um Qasr (Irak), Mayport Naval basin (USA), IJmuiden harbour basin (Netherlands) and Parkhafen (Germany). Computed and measured results are given in **Table 3.4**.

The dry bulk density is assumed to be 400 kg/m^3. The seawater density= 1025 kg/m^3.
The critical velocity for deposition is set to 0.3 m/s.
The horizontal exchange coefficient was set to $f_{1,flood}$= 0.025 and $f_{1,ebb}$=0 for Um Qasr, Parkhafen, Mayport.
The values for IJmuiden case were estimated to be: $f_{1,flood}$=0.05 and $f_{1,ebb}$= 0.1 to represent the relatively large exchange volume (about 20 10^6 m^3/tide) related to the special entrance geometry.
The tidal filling volume is about 7 10^6 m^3/tide. The fresh water drainage volume (V_r) into the IJmuiden harbour basin is about V_r= 4 10^6 m^3/tide or about 90 m^3/s (**De Kok, 2001**).
The exchange volume through the entrance related to the fresh water drainage is given by: $V_{d,a}=(f_m-1)V_r$, yielding a value of about $V_{d,a}$=10 10^6 m^3 per tide for ${}_m$ of about 3.

The density difference in the IJmuiden case was set to 0.25 kg/m^3 (ρ_o= 1015 kg/m^3) to give a density-related exchange volume of about 10 10^6 m^3 per tide.

The computed siltation values are in surprisingly good agreement with the measured siltation rates/dredging rates for all cases (within factor 2). To obtain better agreement with measured values, the mud concentration outside the basin can be calibrated.

Harbour	**$b_{entrance}$ b_{basin} (m)**	**h_o (m)**	**A (m^2)**	**c_{01} c_{02} (kg/m^3)**	**$\Delta\rho_{o,max}$ (kg/m^3)**	**$w_{s,o}$ (mm/s)**	**$\eta_{o,max}$ (m)**	**$u_{o,max}$ (m/s)**	**Sed. volume per year (m^3)**	**Sed. layer per year (m)**
Um Qasr	300 1000	13.5	1.2 10^6	0.2 0.05	1.5	0.3	1.5	1	2.7 10^6 (1.3 10^6)	2.2 (1.1)
Park hafen	515 1000	17	1.5 10^6	0.075 0.025	0	0.3	1.6	1	0.77 10^6 (0.13-0.52 10^6)	0.5 (0.1-0.35)
IJmuiden	500 2000	20	4.0 10^6	0.1 0.02	0.25	0.3	0.8	1	4.3 10^6 (3.2 10^6)	1.07 (0.8)
Mayport	185 500	12.5	0.5 10^6	0.04 0.01	3	0.3	0.75	0.7	0.27 10^6 (0.38 10^6)	0.53 (0.75)

Table 3.4 *Input and output data for four harbour basin cases (measured values between brackets)*

Practical application 2: harbour basin at end of tidal channel

The **SEDHAR.xls** tool can also be used to determine the deposition if the harbour basin area is situated at the end of a tidal channel, see **Figure 3.2**. The banks of the harbour basin may consist of tidal mud flats. Lateral inflow of mud due to wave action (ship waves and wind waves) along these flats may yield a relatively large additional deposition inside the basin.

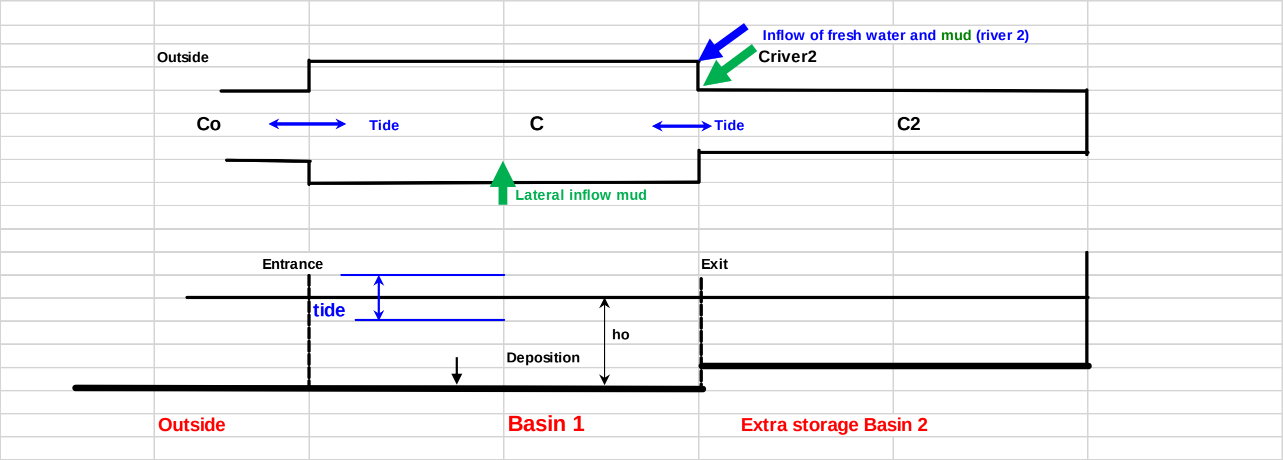

Figure 3.2 *Schematized harbour basin at end of tidal channel (top view and side view)*

The HOLWERD case is related to the ferry mooring basin near the village of Holwerd in the Wadden Sea, The Netherlands. The basin is at the end of a small tidal channel with a length of about 3000 m. The channel width is about 40 m. The channel entrance width is about 30 m. The water depth to MSL is about 4.5 m. The peak channel velocity is about 0.6 m/s. The tidal range is about 2.5 m. The basin area consisting of the tidal channel and mooring basin is estimated to be about 150000 m^2. The extra storage area behind (to the east of) the ferry mooring basin is estimated to be about 300000 m^2. Using these values, the maximum velocity at the entrance of the tidal basin/channel is about 0.6 m/s, which is in good agreement with measured values.

The tidal channel is bordered by mud flats on both sides where lateral influx of mud may easily occur due to surface waves generated by the ferry boats and wind forces. The lateral mud influx can be estimated by $T_{mud, lateral}$= h u c. Using h= 0.5 m, u= 0.01 m/s and c= 0.1 kg/m^3, yields $T_{mud,lateral}$= 0.0005 kg/m/s.

As contimuous dredging is going on, the dry bulk density is assumed to be a relatively low value of 250 kg/m^3. The seawater density= 1025 kg/m^3. Exchange currents are not present (no fluid density differences). The critical velocity for deposition is set to 0.4 m/s. The input data are given in **Table 3.5**.
The computed annual deposition volume is about 1 million m^3/year (see **Table 3,54**) including lateral inflow of mud, which is somewhat smaller than the observed value of 1.5 million m^3/year. The total lateral inflow of mud is estimated to be about 0.2 million m^3/year.

Harbour	**$b_{entrance}$ b_{basin} (m)**	**h_o (m)**	**A_1 A_2 (m^2)**	**c_{01} c_{02} (kg/m^3)**	**$\Delta\rho_{o,max}$ (kg/m^3)**	**$w_{s,o}$ (mm/s)**	**$\eta_{o,max}$ (m)**	**$u_{o,max}$ (m/s)**	**Sed. volume per year (m^3)**	**Sed. layer per year (m)**
Holwerd	30 40	4.5	$1.5\ 10^5$ $3.0\ 10^5$	0.5 0.1	0	0.5	1.25	0	$1.0\ 10^6$ ($1.5\ 10^6$)	6.7

Table 3.5 *Input and output data for harbour basin Holwerd (measured value between brackets).*

3.3 Flushing of small-scale tidal habour basins

The deposited sediments in small-scale basins can be resuspended by mechanical agitation (stirring) and removed from the basin by tidal flushing.
The numerical model based on Eqs. (3.1) to (3.6) has been used to study the flushing process for a basin with characteristics: b= 20 m, h_o= 5 m, A= 100000 m^2, $\eta_{o,max}$ = 1.5 m, $u_{o,max}$ = 1 m/s, $\Delta\rho_{o,max}$ = 3 kg/m^3, ρ_o= 1015 kg/m^3, c_{o1}= 0.1 kg/m^3, c_{o2} = 0.02 kg/m^3, w_s= 0.0003 m/s, ρ_d= dry bulk density of bed material= 400 kg/m^3, T= tidal period = 43200 s (12 hours).

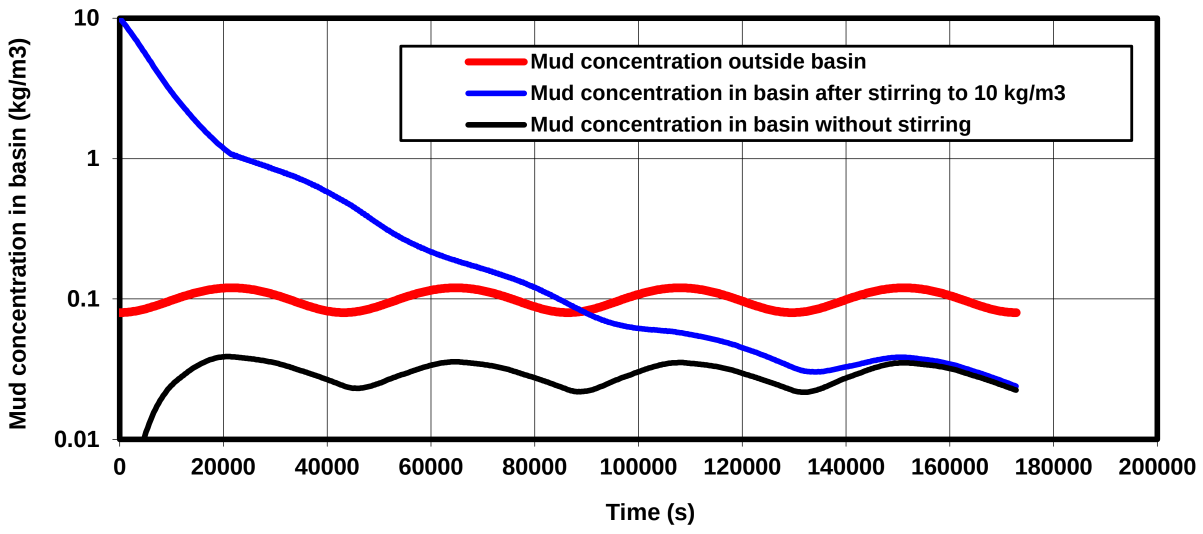

Figure 3.3 *Effect of mechanical stirring and tidal flushing on mud concentration inside basin*

The computed mean annual deposition of mud in this basin is about 35,000 m^3. It is assumed that the mud concentration in the basin can be quickly (within one tide) raised to a value of 10 kg/m^3 (much larger than the concentration outside the basin) by mechanical stirring of the deposited bed material. The computed mud concentrations are shown in **Figure 3.3**. The mud concentration inside the basin returns to its equilibrium value after about 4 tides (2 days). The computed total sediment leaving the basin through the entrance due to flushing is about 3500 m^3 after 4 tides (2 days), which is about 10% of the annual deposition. Hence, the total annual deposition rate can be removed in about 20 days (say about one month; stirring should be applied every two days).

4 Control measures to reduce siltation and dredging in harbour basins

Many harbour basins along (tidal) rivers and coasts suffer from siltation and dredging is required to maintain navigability. Often the fine sediments deposited in harbour basins are contaminated requiring relatively high dredging costs. Small craft harbours such as marinas are from an economic point of view much more vulnerable than commercial harbours and may even become in danger of closing down if no measures for reducing siltation are taken.

In river harbours the major cause of siltation is the water and sediment exchange due to horizontal eddies generated in the entrance of the basin. Mitigating measures should be focused on the streamlining of the entrances so that the generation of eddies and dead water zones is suppressed.

In most tidal harbour basins the major source of sediment input is the effect of tidal filling and density-induced currents. Hence, the mitigating measures should therefore be aimed at minimizing the sediment input during the flood phase of the tidal cycle. Furthermore, the retention time of the suspended sediment in the basin should be decreased as much as possible.

Basically, the reduction of the siltation and associated dredging in the basin requires:

Reduction of water exchange volume:

- construction of rectangular entrance with minimum dimensions (width and depth);
- streamlining of entrance geometry to reduce the generation and strength of eddies and associated horizontal mixing and exchange processes;
- reduction of the density-differences between the main channel and the harbour basin; the input of a relatively large discharge of fresh water (drainage water) into the harbour basin should be reduced as much as possible to reduce density differences;
- construction of entrance structures to reduce water exchange (Entrance Flow Optimisation Structures; EFOS);
- closure of entrances (side entrance by gate or dam; head entrance by a lock);
- definition of nautical depth larger than hydraulic depth (vessels can sail through soft stationary mud layer; surface of soft mud layer is hydraulic bed; bottom of soft mud layer is nautical bed):

Reduction of sediment input of basin:

- reduction of sediment concentration of water entering during the flood phase of the tidal cycle; the basin should be filled as much as possible with water from the upper part of the water column where the sediment concentrations are smallest;
- reduction of the retention time of the water in the basin (to reduce the trapping efficiency) by streamlining of the entrance geometry (removal of eddies and gyres).

The basin entrance needs to be wide to permit the safe passage of vessels, but at the same time the water exchange volume and hence the siltation rates increase with increasing width and depth of the entrance.

Various methods are available to reduce the siltation and associated dredging:
1. selection of appropriate site (new basin);
2. definition of proper nautical depth;
3. improvement of entrance geometry;
4. closure of side entrance;
5. construction of entrance sill;
6. current deflection wall;
7. upstream pile screen;
8. silt curtain;
9. resuspending systems.

Hereafter these methods are discussed in more detail.

4.1 Selection of site location

When a new harbour basin is projected in a certain target area, the available alternative locations should be evaluated taking the following considerations into account:
- the site of an interior harbour basin should be located beyond the maximum salt intrusion point (turbidity maximum) to avoid the occurrence of density differences between the water outside and inside the basin; a coastal harbour should be relatively far away from a fresh water outlet (river mouth); there should be no fresh water outlet in the basin;
- the sediment concentrations in the adjacent main channels (outside the interior basin) should be as low as possible; areas with relatively large concentrations of relatively fine sediments (muddy coasts) should be avoided;
- the longshore transport rates updrift of a coastal harbour basin should be small; areas with relatively coarse materials (coarse sand and gravel) on the downdrift side of headlands are favourable;
- the site should be selected far away (and especially not downdrift) from shoaling areas such as the inner region of a bend, the outlet of a river, large-scale shoals and sand banks, eroding cliffs, dead-water zones (corner areas of lakes, basins, etc.), slowly moving eddy structures, disposal sites of dredged materials, etc;
- the site should always be updrift of eroding areas.

If possible, the basins and berthing places should be selected at sites where the flow velocities just remain above the critical velocity for deposition (say 0.5 m/s). Generally, this can be achieved by the construction of quay walls along the banks of the main channel or the construction of open finger piers perpendicular to the river banks. Blind-ending basins will always suffer from siltation due to the presence of eddies and dead water zones. An additional side or back entrance (outlet) to generate larger flow velocities in the basin may lead to a decrease or increase of the siltation rate depending on the strength of the flow generated in the basin. If the velocities are not large enough, the passage of suspended sediments over the full length of the basin may easily lead to a substantial increase of the siltation (**Nasner, 1997**).

4.2 Definition of nautical depth

In many basins the bed consists of muddy materials and the transition from water to bed is not sharp (as in sandy conditions), but instead shows a discontinuous gradient zone over a layer of 1 to 3 m with densities of 1050 to 1500 kg/m^3 (**Kirby, 1994**). Vessels can sail through fluid mud with a wet bulk density up to 1200 kg/m^3. Hence, the navigation depth can be defined as the level at which the density is 1200 kg/m^3. This definition requires a quick and accurate method to determine density profiles. Traditional echo sounding instruments cannot be used because these instruments detect echoes from various levels of poorly consolidated fluid mud. The question then is which of these echoes should be taken to represent the bed. The development of a continuously traversing density gauge (based on gamma backscatter) has solved this problem and provides an easy method to determine the nautical depth of 1200 kg/m^3. By applying this method, the available draft in fluid mud conditions can be extended with values up to 3 m resulting in less dredging needs. The allowable draft in harbour basins can be further extended by agitation dredging based on stirring of consolidated bed materials to lower the nautical bed level.

4.3 Improvement of entrance geometry

The effect of a blind-ending harbour basin situated along a channel often is that areas of reduced flow or eddying flow are produced in the entrance so that enhanced siltation occurs in the place where it is least required. Siltation rates are usually greatest on spring tides when sediment concentrations are greatest in the main flow channel. Eddy zones are particularly bad since sediment is drawn into them by secondary flows and their unstable nature makes navigation uncertain. Old structures (jetties) should always be removed if they generate large, slow moving eddies near the harbour entrance. So, harbour entrances should be streamlined to reduce eddies and dead-water areas where shoaling can occur. Several gyres (eddies) and dead zones can be present in a harbour basin, depending on the length-width ratio of the basin (length normal to main flow direction; width parallel to main flow direction). More gyres occur when the length-width ratio is larger than about 2. In a rectangular basin the primary gyre is the driving force of a possible secondary gyre. Where possible, harbour basins should be open on both ends to permit the through-flow of water and sediment, provided that the velocities are sufficiently large (>0.5 m/s). Otherwise, it is better to design a closed-end basin.

As the entrance has a significant effect on the water exchange related to horizontal circulation, the width and depth of the entrance should be as small as possible taking the nautical requirements into account.

Jenkins (1981) studied the effect of various entrance geometries of a basin perpendicular to the main channel flow on the water exchange volume related to horizontal circulation, based on experiments in a laboratory scale model. Specifically, a study was made of the effect of projecting “spurs” (training walls) at the corners of the basin and parallel to the main channel (**Figure 4.1**). The spur heads were rounded.

The experimental results show:

- a spur at the upstream corner is much more effective in reducing the water exchange than a spur at the downstream corner; the latter tends to stabilize a strong and stable eddy at the upstream side of the basin;
- a spur with a length of L_1= 1/3B (B= width of entrance) situated at the upstream corner of the entrance yields a significant reduction of the water exchange due to horizontal circulation; an additional spur with a length of L_2= 1/3B at the downstream corner of the basin does not further reduce the water exchange and is therefore not effective.

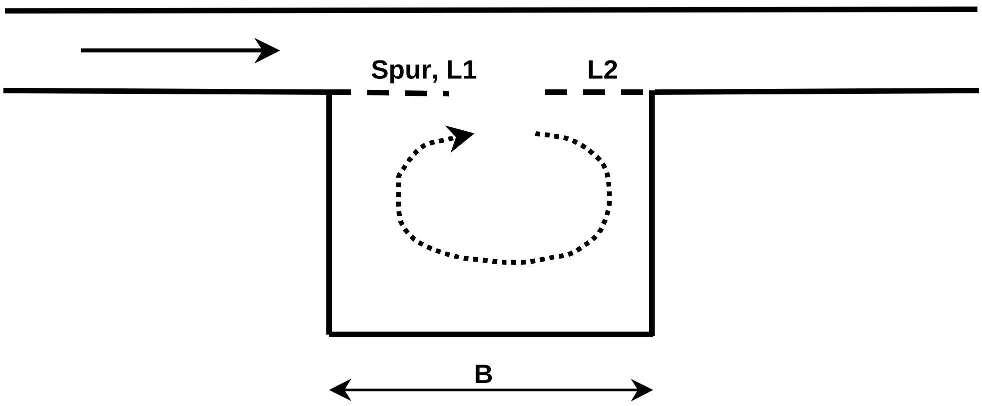

Figure 4.1 *Effect of entrance geometry on water exchange due to horizontal circulation*

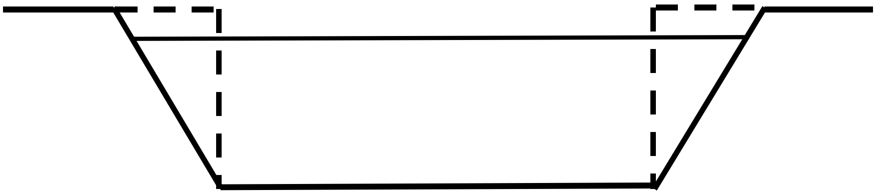

Figure 4.2 *Spurs at corners of trapezoidal cross-section of entrance*

When the entrance of the basin has a trapezoidal shape (**Figure 4.2**), the sides of the entrance should be designed with spurs to obtain a rectangular entrance to reduce the water exchange volume as much as possible, This measure is very effective in the case of a relatively small width. Generally, the sloping sides are not important with respect to navigation through the entrance and should therefore be removed (closed). Basically, it means a small reduction of the effective entrance width.

Langedoen et al. (1994) studied the influence of the shape of the entrance of an interior tidal harbour basin on the horizontal exchange between the main flow and the basin based on measurements in laboratory scale models. The water depth was constant in most tests and varied sinusoidally in some tests to simulate tidal flow. Various basin geometries were studied: perpendicular to the main channel and at angles of 45^o and 135^o between the main flow direction and the basin axis (**Figure 4.3**). The study results can be summarized as:

- the filling of the harbour basin accelerates the development of the eddy (gyre) in the entrance, whereas the emptying of the basin retards or even prevents the development of the eddy;
- a narrowed entrance (by spurs) highly reduces the exchange of mass between the basin and the main channel at slack water, but enhances it during maximum current;
- the size of the eddy in the entrance, the eddy velocities, the width of the mixing layer and the horizontal exchange volume are much larger for an angle of 45^o than for an angle of 135^o.

A large gyre almost occupying the entire harbour area and smaller secondary gyres in the corners were present for an angle of 45^o. The primary gyre was about 50% smaller for an angle of 135^o. The tide-averaged exchange coefficients (f_1) varied between 0.019 and 0.023 for various geometries (perpendicular and oblique; with and withour spurs). The tide-averaged values are remarkably close, although the variation over time of the flow conditions and exchange processes are rather different in each entrance geometry. **Booij (1986)** studied exchange coefficients for steady flow and found values of 0.02 for a basin angle of 135^o, 0.032 for an angle of 90° and 0.05 for and angle of 45°. Thus a basin angle of 135° leads to considerably less exchange of water between the basin and the main outside channel than an angle of 45°.

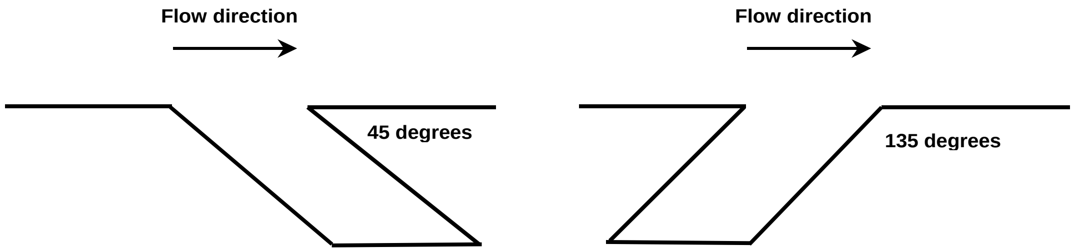

Figure 4.3 *Effect of basin angle on horizontal circulation*

The f_1-coefficients of various entrance geometries are shown in **Figure 4.4**. The reference case is a rectangular basin perpendicular to the main flow direction. The exchange coefficient for this type of basin is about f_1=0.03 (**Booij, 1986**).

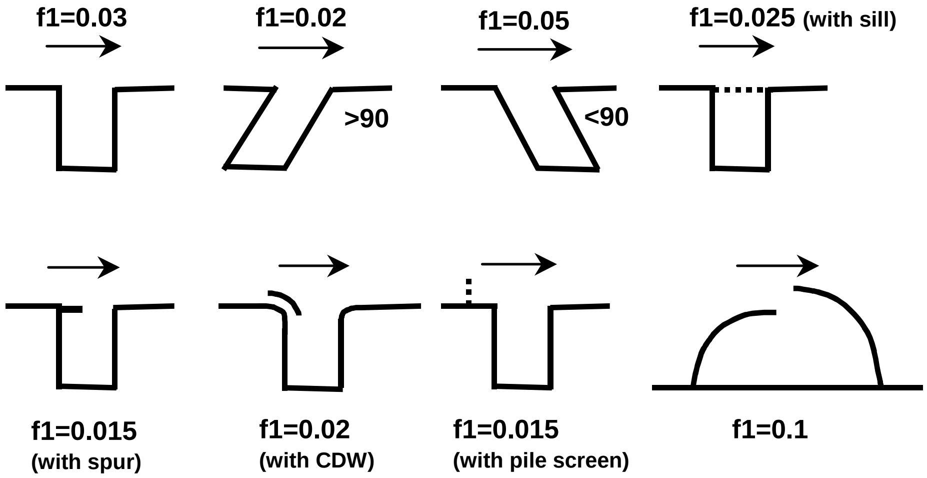

Figure 4.4 *Various entrance geometries and associated horizontal exchange coefficients (f_1)*

4.4 Closure of side or backentrance

It is often believed that the siltation in a basin with two entrances (one at each end of the basin) is less than that in a blind-ending basin (one entrance), because in the former case the flow goes through the basin keeping the sediments partly in suspension. This principle only works if the flow velocities are sufficiently large (larger than about 0.5 m/s), but it also means that the basin can be filled from two directions and that the sediments may pass through the entire basin.

Nasner (1997) studied the effect of the closure of a side entrance on the siltation in the Neustädter basin (total area of about 650,000 m^2) of the harbour of Bremen in Germany (**Figure 4.5**). The harbour of Bremen is situated along the Weser River at about 50 km from the sea (beyond the maximum salt intrusion point). The

mean tidal range is about 4 m; the tidal range decreases slightly with increasing fresh water discharge. The flood velocities are as large as 1 m/s in the main channel. The side entrance was closed in 1992 to reduce the maintenance dredging in the basin (see **Table 4.1**). Before the closure the flood flow passed the entrance and the middle part of the basin and left the basin through the side entrance. The maximum siltation was about 2 m per year in the end part of the basin. The overall siltation was 0.4 m per year for the entire basin area (before closure). Based on bed samples, the deposited materials consisted mainly of fine sand (0.2 mm) in the main entrance of the basin and mud (0.01 to 0.02 mm) in the middle and end basins.
After closure of the side entrance the basin became a blind-ending basin with eddy structures in the entrance resulting in increased siltation in the entrance of the basin due to exchange processes with the flow in the main channel. The flow velocities in the middle and end basins decreased considerably yielding less supply of sediment and hence less siltation.

Basin	Siltation volume before closure (1967-1991) (m^3/year)	Siltation volume after closure (1992-1996) (m^3/year)	Difference (percentage %)
Entrance	35 000	49 000	+17
Middle	160 000	89 000	- 45
End	62 000	19 000	- 70
Total	257 000	157 000	- 40

Table 4.1 *Siltation volumes in Neustädter basin of harbour of Bremen, Germany*

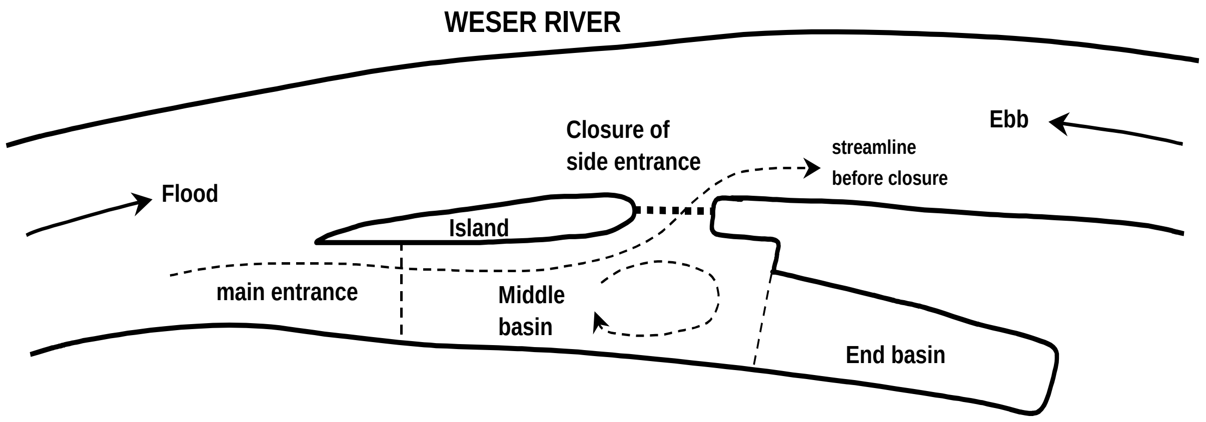

Figure 4.5 *Closure of side entrance of Neustädter basin of harbour of Bremen, Germany*

4.5 Construction of entrance structures

Sill

The construction of a sill at the entrance can be used to reduce siltation due to density currents in relatively small-scale enclosed harbour basins located in high tidal range areas (see **Figure 4.6**). The sill can be used to reduce basin excavation costs, but it restricts navigation in and out of the basin to times of higher tidal elevation. Sometimes, these basins are called “half-tide” harbours (**Everts, 1980**).

Generally, the draft of the vessels is restricted to about 3 m (tidal range of 5 m, sill of 2 m above MLLW). The tidal variation inside the basin should be nearly in phase with, and of the same amplitude as that outside the basin. The minimum basin level is equal to the sill level. The sill reduces the exchange volume related to vertical circulation (density-induced curents) and due to turbidity currents. Suspended sediments inside the basin settling below the sill level are considered to be trapped. Horizontal circulation within the basin at high tide is generally too small to cause resuspension of deposited sediments.

The operation of a movable sill turning around a hinge point at the bottom based on the pumping of air (upraising to vertical position) or water (sinking to horizontal position) may be an alternative solution for entrances of small-scale harbour basins.

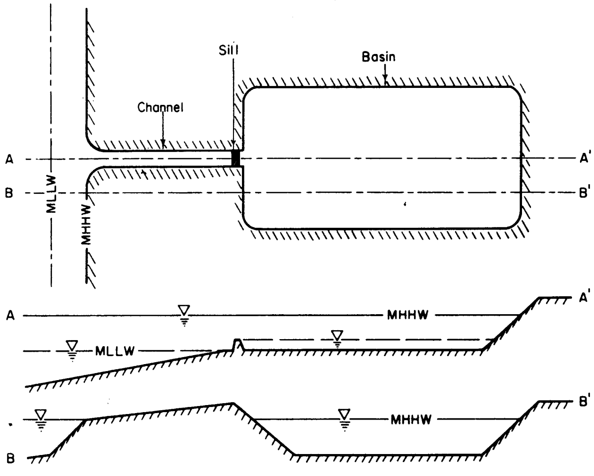

Figure 4.6 *Harbour basin with sill at entrance to reduce siltation and excavation for small-scale basins*

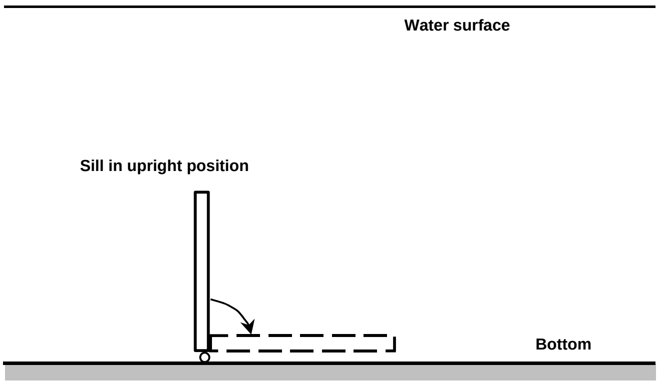

Figure 4.7 *Movable sill to reduce siltation in small-scale basin*

In the case the sill extends above MLLW, the tidal filling volume reduces to: $V_t= (2\eta - z_s)A$ with z_s= sill level above MLLW. The exchange volumes due to horizontal and vertical circulation are reduced due to the reduction of the effective water depth at the entrance. Furthermore, the density currents during ebb flow are partly eliminated.

Everts (1981) reports that the trapping efficiency during the flood phase is somewhat larger (about 15%). In the case of a linear tidal variation of the depth-mean concentration (c_o) with a lower value at the beginning (initial) of the flood phase, increasing to a maximum value at mid flood tide and decreasing again to the initial value, the trapping efficiency factor will be somewhat reduced (about 10% to 15%; Everts, 1981).

Van Schijndel and Kranenburg (1998) studied the effect of a sill on the water exchange between a non-tidal river and a small-scale harbour basin, based on experiments in a laboratory scale model of an existing harbour. A straight sill in the basin entrance was found to be much less effective than an inward curved sill which followed the contours of the eddy generated in the basin entrance (**Figure 4.8**). This latter type of sill will create a situation that the circulation zone is kept fixed in an area between the curved sill and the river bank line (about 70% reduction of exchange volume). The water exchange was further reduced (to about 80%) by extending the downstream part of the sill into a dam with the crest level above the water surface (narrowing of entrance width).

Lock
The most drastic solution at the entrance of a basin is the construction of a lock, which may offer a good solution for relatively large basins in conditions with high tidal ranges, salinity-induced density currents and large mud concentrations (turbidity maximum). The advantages of a lock are: (1) complete closure of the basin reducing maintenance dredging, (2) constant water level in the basin and (3) reduction of salinity intrusion in the basin. Disadvantages are: (1) time required for vessels to pass the lock and (2) relatively large construction and operational costs.

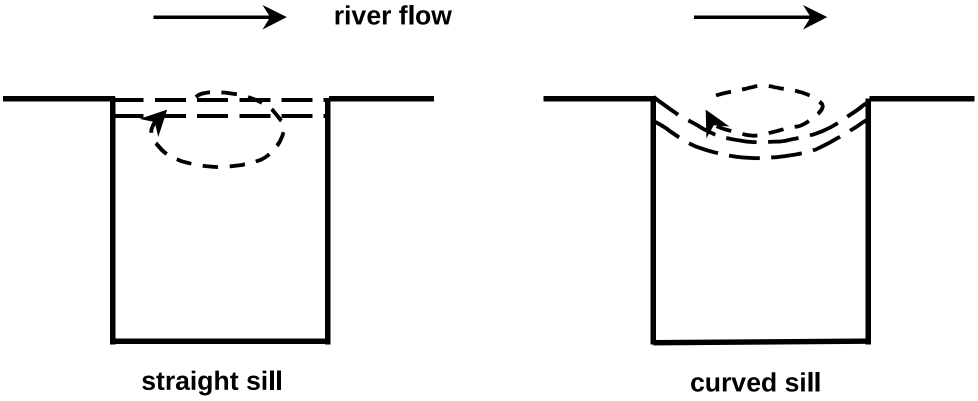

Figure 4.8 *Curved and straight sills in small craft harbour basins*

4.6 Current deflection wall at upstream corner of basin entrance

Homogeneous fluid density
The current deflection wall (CDW; see **Figures 4.9 to 4.12**) has been designed by the harbour authorities of Hamburg (Germany) to reduce the siltation volume in the entrance region of some basins (**Winterwerp et al., 1994; Schwarze et al., 1995**). The harbour of Hamburg is situated along the tidal Elbe River at about 100 km from the sea and well beyond the region of salt intrusion (no density currents). The tidal range is between 3 and 4 m. The entrance depth of the basins is about 15 to 17 m. The peak tidal discharge is of the order of 5000 m^3/s; the river discharge (fresh water) varies between 200 and 2000 m^3/s depending on the season (rainfall). The cross-section-averaged velocities are roughly: 0.75 m/s (river discharge of 2400 m^3/s) and 0.55 m/s (river discharge of 200 m^3/s) during the ebb phase and 0.65 m/s (high river flow) and 0.45 m/s (low river flow) during the flood phase of the tide. The peak velocity during the flood phase near the entrance of the Parkhafen basin is about 1 m/s. The river carries fine-grained sediment in suspension at an annual mean concentration of about 0.05 to 0.1 kg/m^3, particularly during the flood phase of the tidal cycle. The sediment

concentrations vary over the depth; the bottom concentrations (at about 0.5 m above the bed) are a factor 4 to 5 larger (0.2 to 0.3 kg/m^3) than the surface concentrations. The sediment concentrations near the bed are about the same during the ebb and flood phases of the tide, but the concentrations in the upper part of the flow are markedly larger (factor 1.5 to 2) during the flood phase of the tide due to sediment entrained in the mouth of the estuary. Siltation in the harbour basins is maximum in conditions with relatively low river discharges, when the tide can better penetrate into the harbour area (relatively large mud concentrations entering from seaside; thin fluid mud layers were also observed during periods with low river discharges; **Christiansen and Kirby, 1991**). Another basic feature is that the siltation in the entrance of the harbour basin (see **Figure 4.11**) is about 60% to 85% of the total siltation in the basin.

The main purpose of the CDW is to:

- prevent flow separation at the upstream corner of the entrance (**Figure 4.10**);
- suppress the generation of eddies in the entrance region (**Figure 4.10**) and the associated siltation 'pile' in the middle of the eddies (often up to 3 m per year); to spread out the deposited sediments more evenly requiring less frequent dredging to maintain the required navigation depth;
- reduce the exchange volume related to horizontal circulation and hence the input of sediment into the basin;
- reduce the retention time of the sediments in the basin due to an improved advective inflow and outflow of water; the presence of large-scale eddy structures in the entrance region will hamper the inflow and outflow of water and thus increase the retention time of the sediments.

The CDW is located at the upstream corner of the entrance of the basin with respect to the flood current and can easily be combined with a sill between the wall and the bank of the river to reduce the inflow of high concentration water (turbidity layer) from the bottom layers. The sill (with a height of about 30% of the local depth), as shown in **Figure 4.9**, diverts the water away into the main channel. The optimum design of the CDW consists of two curved wall sections with a gap between the two sections to obtain the most favourable flow pattern in the entrance. The nose of the CDW should be equipped with a streamlined nose profile to prevent flow separation and eddy generation at the edge. The total length is about 30% to 40% of entrance width. The opening between the wall and the river bank is of the order of the 10% to 15% of the width of the main river channel; the walls should be placed as close as possible to the river bank outside the nautical cross-section of the main channel. The total volume passing between the CDW and the river bank should be somewhat larger than the tidal basin volume. To accommodate sufficient flow along the bank, it may be necessary to steepen the river bank locally.
The CDW has been installed in 1990 near the upstream corner of the Köhlfleet harbour basin in Hamburg resulting in a 30% reduction of the deposition volume in the entrance of that basin, as shown in **Figure 4.11**.

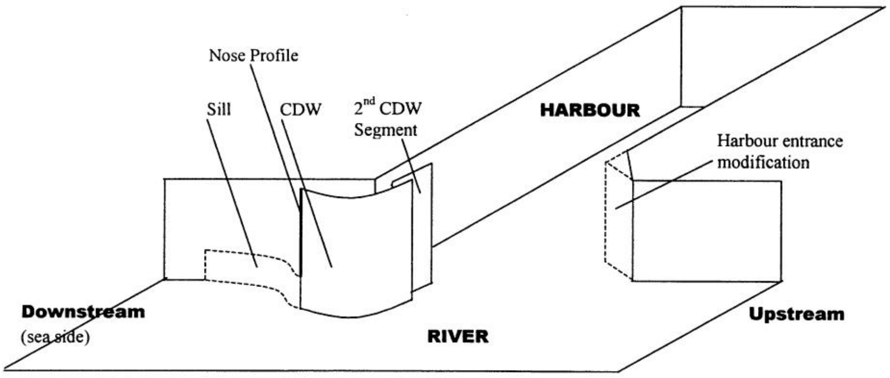

Figure 4.9 *Current deflection wall (CDW) with bottom sill between wall and river bank (Van Leeuwen and Hofland, 1999)*

The effect of a CDW critically depends on the local hydraulic conditions and the geometry of the entrance. The proper design of a CDW should be based on experiments in a laboratory scale model (**Delft Hydraulics, 1992 and 2001; Van Leeuwen and Hofland, 1999; Crowder, 2001 and 2002**). An incorrect design may even cause deterioration of the flow patterns by generating additional eddies and siltation. Based on detailed tests for the Parkhafen entrance geometry, the horizontal water exchange could be reduced significantly. Based on laboratory experiments in a schematized harbour basin, **Crowder (2002)** has shown that the eddy circulation in the entrance can be significantly reduced by using an upstream CDW for basin angles of 45° and 90°.

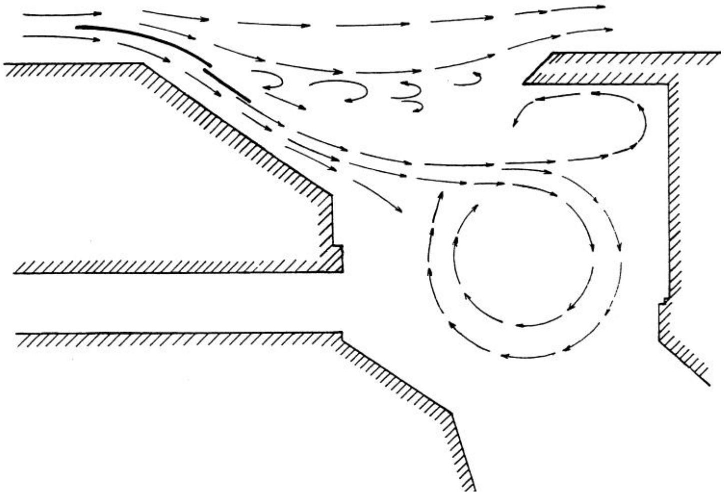

Figure 4.10 *Streamline patterns in basin entrance due to presence of current deflecting wall at upstream corner of entrance (large-scale eddy/gyre is pushed inside basin)*

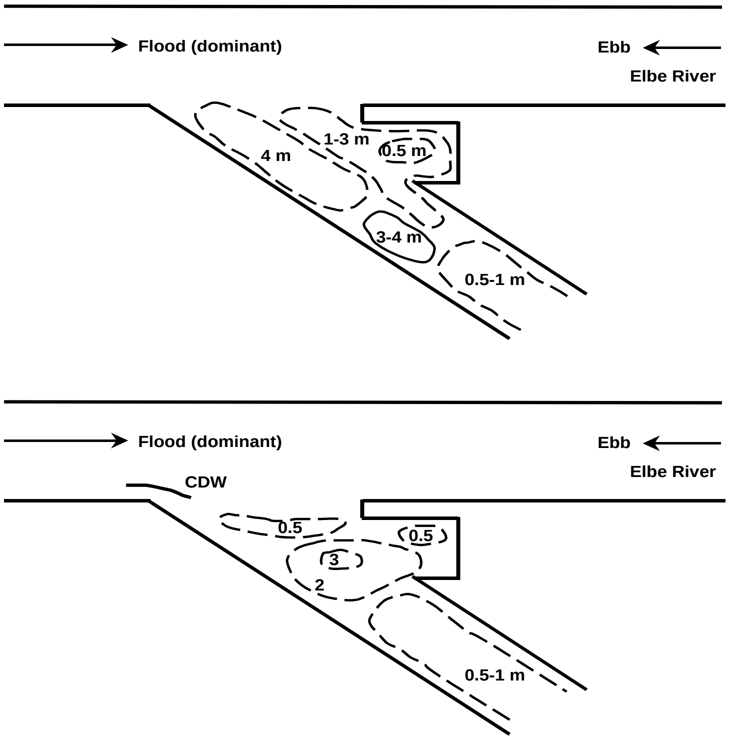

Figure 4.11 *Siltation patterns (metres per year) in Köhlfleet basin of Hamburg harbour, Germany*
Top: Without current deflection wall
Bottom: With current deflection wall on the upstream side with respect to flood current

Non-homogeneous fluid density (salinity effects)

The influence of the presence of a CDW (including a sill at the bottom, see **Figure 4.12**) on the exchange volume in conditions with saline sea water penetrating into the harbour basin was studied by **Van Leeuwen and Hofland (1999)** and **by Crowder (2001, 2002)**. They performed experiments in a laboratory setup for a schematized situation. The basin was situated at an angle of 45° with the main flow direction (flood) in the channel and the ratio of width and depth at the entrance was about 4.

Based on dye measurements, the schematized flow pattern during the flood phase of the tide is shown in **Figure 4.12**. The following phenomena do occur:

- the upper portion (low-density and low-concentration) of the water passing between the CDW and the river bank flows into the basin entrance against the outgoing density current in the surface layer of the basin;
- the lower portion of the water passing between the CDW and the river bank flows downwards behind the sill;
- the (high-density) water near the bottom is deflected into the river around the sill;
- a complex three-dimensional vortex street is generated in the bottom section of the entrance, which reduces the inflow of high-density water in the bottom section (lower 25% of depth) during flood tide by about 40%;
- the density difference between the main channel and the basin increases slightly (5% to 10%) due to the inflow of low-density water between the CDW and the river bank resulting in a slight increase of the density-related exchange volume (especially manifest at slack high water at the end of the flood period);
- the total exchange volume over the full depth and over the full tidal cycle was not changed much by the presence of the CDW; hence, the decrease of the near-bed inflow of saline water during flood is compensated by the increase of the inflow during slack tide at the end of the flood period (increase of density difference between basin and main channel); the reduced inflow of relatively high-concentration water during flood and the increased inflow of relatively low concentration water during slack tide at the end of the flood period may lead to less overall siltation (exchange volume is about constant but tide-averaged concentration is lower).

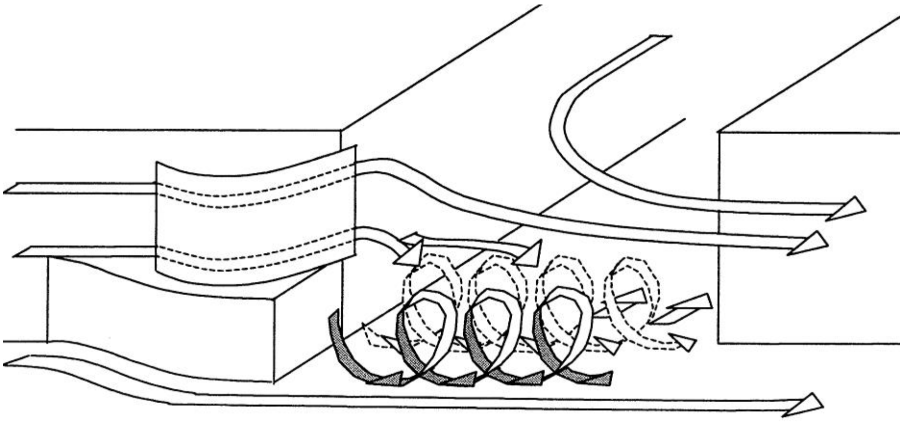

Figure 4.12 *Current deflection wall including a sill in conditions with salinity differences (Van Leeuwen and Hofland, 1999)*

The action of the vortex street in the basin entrance considerably reduces the inflow at the bottom section in the laboratory scale model (**Van Leeuwen and Hofland, 1999**) but it should be pointed out that the entrance width was relatively small (width-depth ratio of 4). In field conditions the width-depth ratio will be about 10 to 20 and then the vortex street induced by the CDW and sill will be considerably less effective. Probably, the density-related exchange volume will only be slightly reduced in practical field situations (say 5% to 10%).

Finally, it is remarked that the costs related to the construction of a CDW including a sill may be relatively large (rigid structure is required to withstand flow forces) and should be compared to the savings in dredging costs. In Hamburg harbour where dredging costs (including storage or cleaning of contaminated sediments) are relatively high and density-induced exchange currents are not important, the construction of a CDW appears to be an economic solution.

4.7 Upstream pile screen

Van Schijndel and Kranenburg (1998) studied the effect of an upstream permeable pile screen normal to the river flow on the water exchange volume into a small craft harbour basin along a (non-tidal) river, based on experiments in a laboratory scale model of an existing harbour. The presence of a permeable pile screen extending over a small distance (not more than 10% of the river width) into the river prevents the generation of large eddies typical of mixing layers in the entrance of the basin. The change in turbulence structure of the mixing layer decreases the velocities in the primary gyre, thereby reducing (by about 50%) the water exchange between river and harbour basin.
The length of the pile screen should be larger than 25% of the entrance width, but the length cannot be larger than say 10% of the river width; otherwise it will hinder the navigation in the river. The screen should be placed at a distance of about 10% to 15% of the entrance width from the upstream corner. The spacings between the piles should be variable from zero near the bank to a value equal to the pile thickness (about 0.3 to 0.5 m) at the head of the screen. The water exchange reduction for the permeable pile screen was insensitive to small changes in the design. The permeable pile screen will reduce the siltation in the harbour basin, but the siltation in the lee area of the pile screen may be relatively large and may reduce the navigation depth in the outside area of the basin entrance.

4.8 Silt curtain

Various types of silt curtains have been used in the entrance of harbour basins:
- air bubble barrier;
- flexible barrier blocking the entrance in the lower part of the water column (**Figure 4.13**)

Air bubble curtains have been used in attempts to reduce silt intrusion. These systems provide a rising flow of air bubbles along a line in the basin entrance with the aim to increase vertical mixing and to alter the water and sediment circulation in such a way that the sediments do not penetrate in large quantities into the basin. Field experiments have however shown that air bubble curtains are not very effective in practice (**Kirby, 1994**).

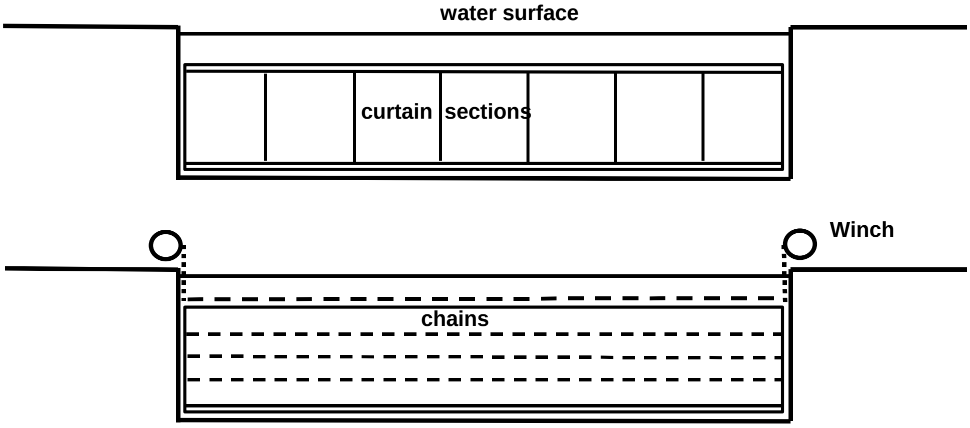

Figure 4.13 *Silt curtain in basin entrance*

A flexible curtain consisting of hypalon was used in one of the naval basins along the Mare Island Strait (**Jenkins et al., 1980**) with an entrance width of about 80 m and depth of about 10 m. The curtain partionated the basin off from the main channel. The curtain extended form the bottom up to the mean low water level. The gap over the curtain (about 1 to 2 m) allowed the tidal filling of the basin with low-concentration water.

The curtain was constructed in 13 sections, each about 6 m in length. The hypalon curtain material on each section was equipped at the lower end with a pipe (0.4 m diameter) filled with concrete to function as anchor weight. The 9 m high curtain sections were supported vertically in the water by curtain bouys constructed from pipes (0.4 m) filled with poly-eurathane foam. A pair of air-filled pipes (pvc) was fitted to the curtain bouys to trim the buoyancy against additional water absorption by the foam and the concrete of the anchor weight. To raise the curtain, a second set of buoys at the surface was used. At high tide the curtain floats free of the bottom, whence it can be swung open into the entrance by towing behind a small tug. At low tide the surface buoys are released to ensure that the anchor weight remains at the bottom during the operational conditions. The surface buoys are connected again to the curtain to raise it at high tide.

Another option for a small craft basin is a curtain attached to a steel chain across the entrance. The curtain consist of various horizontal sections which are separated by flexible steel chains as ballast weight. The uppermost chain can be raised and lowered by a winch system on both sides of the entrance. When the curtain is lowered, it will rest on the bottom of the entrance

These types of curtains can only be used in relatively small basin entrances (maximum about 50 m), where bottom currents are relatively low and navigation intensity is low so that the curtain can remain in place for a relatively long period. Small crafts can pass over the curtain. Due to the presence of the curtain the siltation rate in the Naval basin along Mare Island Strait was reduced by about 70%. Most of the observed siltation occurred during the period that the curtain was open for a period of 3 days. The siltation due to tidal filling over the curtain was minimum.
A hypalon silt curtain is incapable of resisting large-scale density currents in strongly stratified systems.
In 1987 a silt curtain was used near the bottom in the entrance of the Botlek basin of the Port of Rotterdam The presence of the curtain reduced the siltation in the basin entrance, but at the same time a mud shoal was formed in front of the curtain reducing navigation depth in that area. Furthermore, the curtain was regularly damaged by passing vessels, which ultimately resulted in the removal of the curtain.

4.9 Resuspending systems

Various techniques aimed at resuspending the bed sediments have been developed. These methods are also known as agitation dredging methods.
The most common methods are:

- mechanical devices such as rakes, harrows, scrapers and hydrofoils;
- water scour jet devices.

The first attempt to control siltation of mud by resuspending freshly deposited layers of fluid mud date back to the Chinese in the 5th century A.D. **Figure 4.14** shows a rolling suspensifier (the Hun Chiang Lung). This device was drawn along the bottom by a vessel or a team of horses proceeding upstream. The teeth on the roller raised clouds of silt and mud which were carried away on the ebbing tide. Harrows and rakes are similar systems drawn by vessels.

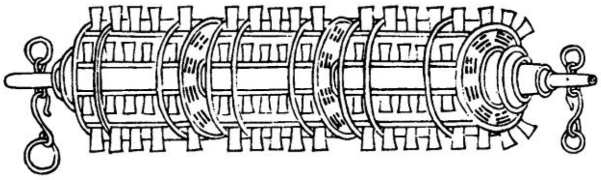

Figure 4.14 *Roller type suspensifier used in China during 5th century A.D.*

Hydrofoils are small wing-type devices (anchored to the bed by a short line), which are suspended in the near-bed flow by lift forces generated by the flow around the foils. The turbulent eddies generated at the trailing edge should scour away the sediments deposited at the bed during the previous slack tide.

A very effective suspensifier is a scour jet array either attached to a fixed structure (quay wall) or drawn by a vessel (**Figure 4.15**). **Jenkins et al. (1980)** show results of a scour jet array attached to pipework mounted on the front face of a quay wall (Mare Island Strait, California, USA). A successful operation requires the presence of a unidirectional current for a sufficient period of time to advect away the sediments which have been resuspended (mainly ebbing bottom currents). The jet nozzles are vulnerable to damage by dragging anchors of moored vessels and should be replaceable by quick-release clamps. Ten equally-spaced jet nozzles (0.07 m diameter) at a spacing of about 7 m were used at a depth of 8 m. The entire pump discharge was operated through each individual nozzle once at a time beginning from the upstream side of the array by use of an automatic switching circuit. Each jet is able to produce a slightly downward-inclined (angle of 30°) discharge velocity of about 8 m/s perpendicular to the quay wall. The jets can scour away deposited sediments over a distance of about 20 m from the quay wall and prevent new accumulation of sediments in that region.

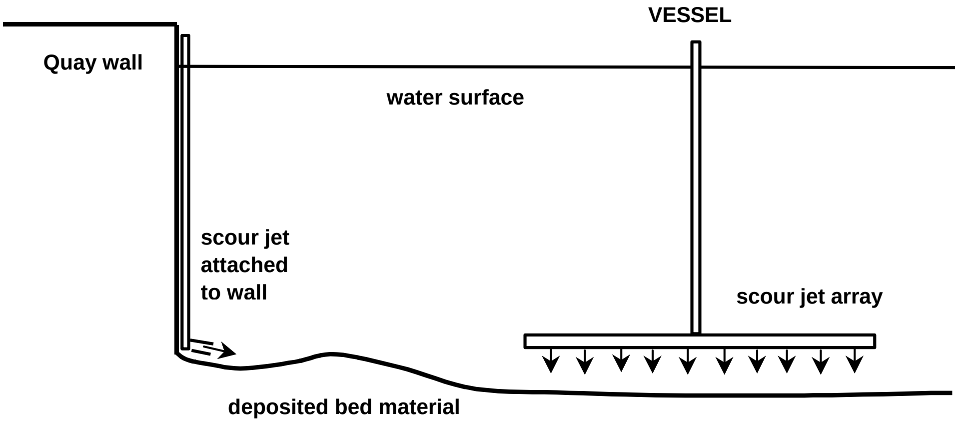

Figure 4.15 *Scour jet systems*

An alternative method is seabed water jetting from a moving vessel (**Figure 4.15**). This method is a type of agitation dredging using conventional techniques, but making no attempt to retain and carry away the spoil. The deposited sediments are entrained by the jet array and dispersed by bottom currents. Furthermore, a high-concentration turbidity current can be generated in the basin which is driven outwards by density-differences at the front of the layer. The process can be enhanced by dredging of a small channel over the length of the basin.

Agitation dredging by scour jet arrays can be very effective in conditions with (**Nasner, 1997**):

- deposits of relatively thick fluid mud (1 to 3 m);
- relatively short, rectangular basin (width of about 200 m; length of about 600 m) with a wide entrance (without a sill);
- hard bottom level of subsoil slightly (about 1 to 2 m) above that of the main channel, so that the turbidity current can be driven out by gravity forces.

5. Design rules for harbour basins

The siltation in a harbour basin depends on:

- concentration just outside entrance,
- tidal volume,
- horizontal (circulation) exchange volume,
- vertical (circulation) exchange volume and,
- the trapping efficiency of the basin.

The concentration, trapping efficiency, tidal volume and vertical exchange volume can hardly be influenced except by changing the location of the basin or by 'hard' entrance structures (such as locks, gates, curtains, sills, deflection walls). Structures can help to fill the basin with water from the upper layers of the water column, where the concentrations are smallest.
If the construction of a structure is not economically feasible, substantial siltation of the order of 1 to 2 m per year can be expected in salt and brackish water conditions. In fresh water conditions the siltation is considerably smaller (0.2 to 0.5 m per year). These values refer to basin-averaged values; the siltation in the entrance area may be 2 to 5 times larger.

From observed siltation rates it can be concluded that harbour siltation in fresh water conditions is much less (factor 5) than in salt and brackish water conditions (**Nasner, 1992**). The generation of stratified flow with a pronounced salt water wedge is a well known phenomenon in the tidal zone of major rivers (tidal volume about equal to fresh water volume over tidal period). The maximum silt and mud concentrations are generally found in the area where the edge of the salt water front is moving up and down the river channel. This zone where soft fluid mud layers are formed due to deposition at slack tides (especially neap tides) is known as the turbidity maximum. Harbour basins should preferably be situated outside this zone to avoid that the deposited fluid mud layers penetrate into nearby harbour basins, requiring major maintenance dredging.

Based on analysis results from siltation data of existing harbour basins and simulation models of harbour siltation, the following design rules should be taken into account to reduce the siltation rates as much as possible:

- the location of a new basin should be outside the salt wedge range (turbidity maximum range) and outside known shoaling areas (inner bend, lee areas, etc.);
- the entrance of a harbour basin should have a rectangular cross-section; additional side or back entrances should not be present and closed if present;
- the entrance width of a harbour basin should be as small as possible;
- the entrance should be streamlined (based on laboratory scale model tests) to reduce the strength and size of the horizontal circulation zones (exchange zones); obstacles (old jetties, old mooring facilities) creating lee areas and eddies near the entrance should be removed;
- the tidal harbour basin should have no inflow of fresh water (from a small river or surface drainage channel) from the landside;
- the nautical depth concept should be applied to allow larger vessels to enter the basin;

- agitation dredging by water jetting is effective in short and narrow basins where the entrance width is about the same as the basin width; the bed level of the basin should be slightly higher than the bed level of the adjacent main channel and the bed should have a gentle slope of about 1 to 500 (upsloping to landside);
- overdredging (buffer zone of 1 to 2 m below nautical bed) is most effective in a large basin with a narrow entrance; the fluid mud near the bed can consolidate in the buffer zone so that relatively thick consolidated material can be dredged by a hopper dredger.

Minimization of siltation and associated maintenance dredging should be an essential element of harbour basin design. Field measurements outside and inside the existing basin or in a similar basin (in case of a new basin) should always be included to obtain realistic boundary conditions, focussing on:

- mud concentration over the seasons and during storm events;
- in-situ settling velocities;
- bed material composition (particle sizes and dry bulk density);
- water levels and tidal currents outside entrance;
- flow patterns in entrance area;
- salinity variations outside and inside basin.

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